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ABSTRACT

PULSAR-I is a 1000 MWe pulsed inductively-driven tokamak design. The reactor uses a helium-cooled SiC composite as a structural material and Li_2O as a breeder. At shutdown, the blanket and shield activities are 693 and 77.9 MCi, respectively. The blanket activity drops by more than two orders of magnitude during the first hour following its replacement. The shield activity drops more slowly than the blanket's. One year after shutdown, the shield activity drops to the same level as the blanket activity. The decay heat generated in the blanket drops from 17.3 MW at shutdown to only 1.14×10^{-3} MW within a week following shutdown. The total of 1.135 MW of decay heat is generated in the shield at shutdown. The shield's decay heat drops by three orders of magnitude during the first day after shutdown. The biological hazard potentials produced in the blanket and shield at shutdown are 33.8×10^9 and 4.3×10^9 m^3 air, respectively. The radwaste classification of the reactor structure is evaluated according to both the NRC 10CFR61 and Fetter waste disposal concentration limits. If the first wall and blanket are disposed of together, the waste package will qualify for Class C Low Level Waste (LLW) disposal. After 30 years of operation, the shield will qualify for disposal as Class A LLW. Assuming a 25 μSv/h limit for hands-on maintenance, only remote maintenance will be allowed at any location inside the containment.

INTRODUCTION

The PULSAR reactor study [1] examined the possibility of obtaining better fusion economics by using a pulsed, inductively-driven tokamak design instead of the commonly proposed steady-state, noninductively driven tokamak designs. The operating cycle consists of a set of 2-hour burn phases separated by a 200-second dwell phase. During the burn phase, plasma confinement is partially sustained by an inductively-driven plasma current.

The safety characteristics of fusion reactors would most probably be dependent on the choice of the structural material. The level of radioactivity induced in any reactor structure depends on the constituent elements of the irradiated material, level of neutron flux and time of irradiation. Low activation materials (LAMs) are an attractive choice because they result in lower levels of off-site doses in case of accidental release of their radioactive inventories during an accident. LAMs can also facilitate better waste management at the end of the reactor life. For these reasons SiC was selected as the main structural material in the PULSAR-I design.

Detailed activation analyses were performed to identify the safety, environmental and radwaste characteristics of the PULSAR-I reactor. As mentioned before, PULSAR-I uses a helium-cooled SiC composite as a structural material. The blanket uses Li_2O as a breeder and beryllium as a neutron multiplier. The activity, decay heat and biological hazard potential (BHP) were calculated for up to 1000 years following shutdown. The waste disposal ratings (WDR) of the reactor structures at the end of their lifetimes were also evaluated. Finally, to assess the possibility of hands-on maintenance, contact dose rates were calculated at selected locations inside the reactor containment.

CALCULATIONAL PROCEDURE

The neutron flux used for the activation calculations was generated by the one-dimensional discrete ordinates neutron transport code ONEDANT [2]. The calculations used a toroidal cylindrical geometry model with the inboard and outboard sides modeled simultaneously. The peak neutron wall loadings on the inboard and the outboard sides are 1.6 and 2.21 MW/m^2, respectively. The analysis was performed for the average peak neutron wall loading of 1.33 MW/m^2. The activation calculations were conducted using the DKR-ICF computer code [3].

The reactor is assumed to operate continuously for 30 full power years (FPY) which corresponds to 40 years of operation at 75% availability. While the blanket was assumed to be replaced every 5.88 FPY, the shield was assumed to stay in place for the duration of the reactor lifetime. The inboard and outboard regions are assumed to extend over the heights of 7 and 10 meters, respectively. Due to the length of the burn time (2 hours) compared to the dwell time (200 seconds), the calculations were performed with the assumption of continuous operation rather than pulsed operation. Although assuming continuous operation does not affect the calculated activities for radionuclides with half-lives much less than the shortest period of continuous operation or much greater than the reactor

Table I
Materials Used in the PULSAR-I Analysis

Inboard	
VV	95% MHT-9
B_4C Shield	15% SiC, 80% B_4C
Al Shell	100% Al
SiC Shield	95% SiC
Blanket	14% SiC, 10% Be, 47% Li_2O
FW	50.6% SiC
Outboard	
FW	40.4% SiC
Blanket	11% SiC, 5% Be, 56% Li_2O
SiC Shield	95% SiC
Al Shell	100% Al
SiC Shield	79% SiC
VV	95% MHT-9

lifetime, the radioactive inventory of radionuclides with intermediate half-lives is overestimated by the inverse of the reactor availability [4]. Therefore, the results for the radioactive inventories could be overestimated by up to 33%.

The structure activation results were utilized in a radwaste classification. The DOSE code [3] was used to calculate the contact doses behind the outboard's first wall, blanket, shield and vacuum vessel. The materials used in the blanket and shield are presented in Table I. The elemental composition of the SiC composite used in this analysis is similar to the one irradiated in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory [5]. The elemental compositions of the low activation ferritic steel (modified HT-9), the beryllium alloy, and the Li_2O breeder are taken from the Blanket Comparison and Selection Study (BCSS) report [6].

RADIOACTIVITY ASPECTS OF PULSAR-I

At shutdown, the blanket and shield activities are 693 and 77.9 MCi, respectively. The high short-term activity induced in the blanket is mainly caused by the decay of ^{28}Al ($T_{1/2}$ = 2.25 min), ^{29}Al ($T_{1/2}$ = 6.55 min), and ^{27}Mg ($T_{1/2}$ = 9.45 min). The blanket activity drops by more than two orders of magnitude, to only 3.98 MCi, during the first hour following its replacement. During the first few days following blanket's replacement, ^{31}Si ($T_{1/2}$ = 2.62 hr), ^{24}Na ($T_{1/2}$ = 14.96 hr), and ^{28}Mg ($T_{1/2}$ = 21 hr) are the major contributors to the activity generated in the blanket. The intermediate-term radioactivity induced in the blanket is mostly due to ^{22}Na ($T_{1/2}$ = 2.605 yr), ^{54}Mn ($T_{1/2}$ = 312 day), ^{55}Fe ($T_{1/2}$ = 2.7 yr), ^{60}Co ($T_{1/2}$ = 5.27 yr), and ^{3}H ($T_{1/2}$ = 12.3 yr). Tritium generated in the SiC structure would easily become the major contributor to the radioactive inventory if it does not diffuse out of the structure. The long-term activity is dominated by ^{10}Be ($T_{1/2} = 1.6 \times 10^6$ yr), ^{14}C ($T_{1/2}$ = 5730 yr), and ^{26}Al ($T_{1/2} = 7.3 \times 10^5$ yr). The blanket's outboard region dominates the inboard region at all times following shutdown. The outboard side of the blanket produces about 70% of the total blanket activity.

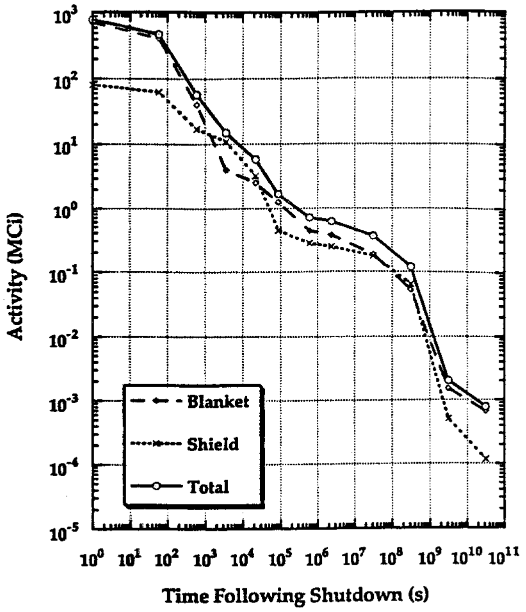

Fig. 1. Activity induced in PULSAR-I structure.

The shield activity drops more slowly than the blanket's. One year after shutdown, the shield activity drops to the same level as the blanket activity. Unlike the blanket, the inboard side of the shield produces more than 55% of the total activity generated in the reactor shield. The shield's short-term activity is dominated by ^{54}Mn and ^{56}Mn ($T_{1/2}$ = 2.6 hr). In addition to ^{54}Mn, ^{60}Co and ^{3}H dominate the intermediate-term activity induced in the shield. The tritium generated in the B_4C shield dominates the radioactivity induced in the total shield during the first 10 years following shutdown. The long-term activity induced in the shield comes from the modified HT-9 steel and is caused by the decay of ^{14}C, ^{93m}Nb ($T_{1/2}$ = 16.1 yr), and ^{94}Nb ($T_{1/2} = 2 \times 10^4$ yr). Fig. 1 shows the total activity induced in the different regions of the PULSAR-I blanket and shield as a function of time following shutdown.

Fig. 2 shows the temporal variation of the decay heat generated in the blanket and shield. The decay heat generated in the blanket drops from 17.3 MW at shutdown to only 0.058 MW within an hour and to 1.14×10^{-3} MW within a week following the blanket replacement. Only the total of 1.135 MW of decay heat is generated in the shield at shutdown. The decay heat drops by three orders of magnitude during the first day after shutdown. In general, the decay heat generated in PULSAR-I is mostly dominated by the same isotopes that dominate the activity. One week after shutdown, the values of the integrated decay heat generated are 8.74 GJ for the blanket and 1.36 GJ for the shield. These values are very small and pose no serious safety hazard in case of coolant loss.

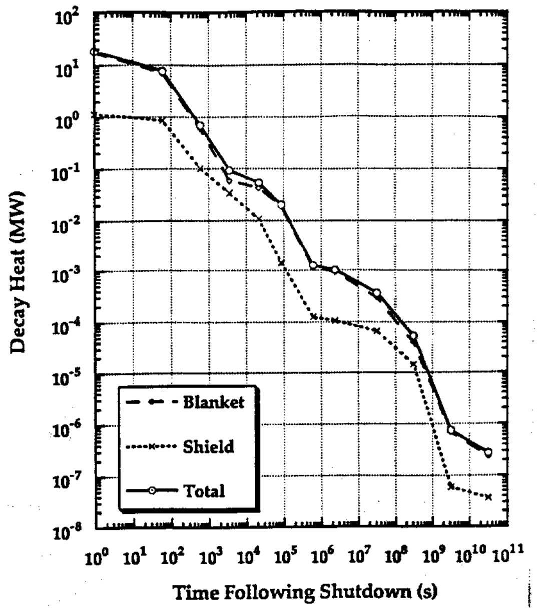

Fig. 2. Decay heat induced in PULSAR-I structure.

The Biological Hazard Potentials (BHP) were calculated using the maximum permissible concentration limits in air for the different isotopes according to the NRC regulations specified in 10CFR20 [7]. The structure BHP in air as a function of time after shutdown is shown in Fig. 3. The blanket BHP at shutdown is 33.8×10^6 km^3 air with about 70% of it contributed by its outboard side. On the other hand, the shield BHP at shutdown is 4.3×10^6 km^3 air with about 55% of it contributed by its outboard side.

WASTE DISPOSAL RATINGS

The different radionuclide specific activities calculated by the DKR-ICF code were used to calculate the waste disposal ratings according to both the NRC 10CFR61 [8] and Fetter [9] waste disposal concentration limits (WDL). The waste disposal ratings for Class A and Class C low level waste (LLW) are shown in Table II. The results in the table are given for both classes with the activities averaged over the total volume of the first wall, first wall & blanket, and shield of PULSAR-I. The values in the table are given for both non-compacted and compacted (between brackets) values. Non-compacted values are based on averaging the specific activities over the total volume of a particular region assuming that internal voids will be filled with concrete before disposal. On the other hand, compacted values correspond to crushing the solid waste before disposal. The 10CFR61 Class A WDR is given after a waiting period of about 10 years to allow for the specific activity of short-lived nuclides ($T_{1/2} \leq 5$ years) to drop below 7000 Ci/m^3. The 7000 Ci/m^3 limit is 10 times larger than the limit specified by the NRC for Class A disposal of short-lived nuclides where the waste form is not specified. In comparison with other isotopes for which limits are given for different waste forms, the factor of 10 is used for isotopes contained in metal waste. Since the NRC regulations do not specify any limit for short-lived activity for Class C LLW, the Class C WDR values were calculated after a 1 year cooling period for both 10CFR61 and Fetter limits.

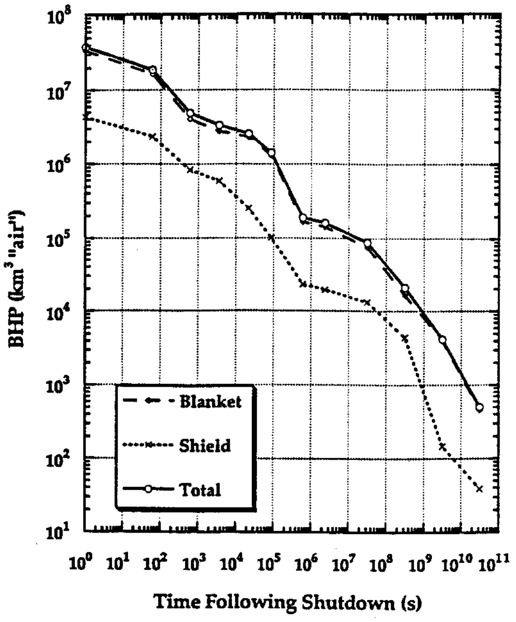

Fig. 3. Biological hazard potential in PULSAR-I structure.

As shown in the table, if the 10CFR61 limits are used, ^{3}H dominates the Class A WDR for the first wall (the level of contribution is shown between brackets). On the other hand, ^{14}C dominates the Class A WDR for the FW & blanket and the shield. The Class C waste disposal ratings are dominated by ^{14}C. If Fetter limits are used, the blanket WDR is dominated by ^{26}Al. ^{26}Al is produced through the ^{27}Al (n,2n) reaction. Aluminum is not a constituent of SiC. However, ^{27}Al is produced via the high energy (n,n′p) reaction. Using the same limits, the shield is dominated by ^{192m}Ir ($T_{1/2}$ = 241 yr). ^{192m}Ir is produced from the iridium impurities in the SiC shield and MHT-9 vacuum vessel. Unless tritium is diffused out of the first wall, it would only qualify for disposal as Class C LLW if the 10CFR61 limits are used. If the first wall and blanket are disposed of together, the waste package would also qualify for Class C LLW disposal. After 30 years of operation, the shield would qualify for disposal as Class A LLW, regardless of the limits used.

CONTACT DOSE

Contact dose rates were calculated for maintenance evaluation. The doses were calculated using the DOSE code, which combines the decay gamma source and the adjoint dose field to determine the contact dose rates at different times following shutdown. The decay gamma source at different times following shutdown was calculated using the DKR-ICF code. The adjoint dose field was determined by performing a gamma adjoint calculation using the ONEDANT code with the flux-to-dose conversion factors representing the source at the location where the dose

Table II

PULSAR-I Waste Disposal Ratings

WDR	FW	FW & Blanket	Shield
Class A	3.1 (6.45)	1.89 (2.94)	0.226 (0.24)
(10CFR61)	^{3}H (100%)	^{14}C (90%)	^{14}C (55%)
Class C	4.1×10^{-3} (8.5×10^{-3})	0.17 (0.26)	1.21×10^{-2} (1.27×10^{-2})
(10CFR61)	^{14}C (100%)	^{14}C (100%)	^{14}C (100%)
Class C	0.41 (0.85)	0.019 (0.03)	0.01 (0.011)
(Fetter)	^{26}Al (100%)	^{26}Al (97%)	^{192m}Ir (90%)

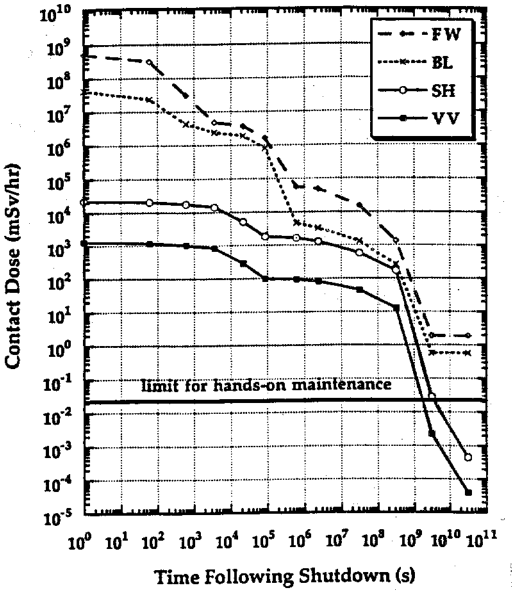

Fig. 4. Contact dose in PULSAR-I.

was to be calculated. The contact doses were calculated at four different locations behind the first wall, blanket, shield, and vacuum vessel of the outboard side. A limit of 25 μSv/hr for hands-on maintenance was used in this analysis, assuming that maintenance personnel work for 40 hours a week and 50 weeks a year. Results in Fig. 4 shows that only remote maintenance would be allowed at any of the locations considered inside the containment building. The contact dose is mostly produced during the first few weeks by the decay of ^{31}Si, ^{54}Mn, and ^{60}Co.

CONCLUSIONS

The PULSAR-I pulsed power reactor has attractive safety and environmental characteristics. The use of the low activation SiC composite as a structural material significantly enhances its safety aspects. At shutdown, the blanket activity is 693 MCi and drops by more than two orders of magnitude during the first hour following shutdown. Unless tritium is removed from the blanket, its activity would greatly outweigh the activity associated with other activation products in the Li_2O breeder. At shutdown, the activity generated in the shield is an order of magnitude lower than the activity induced in the blanket. However, the shield's activity drops more slowly than the blanket's. One year after shutdown, both blanket and shield generate a similar amount of activity. The decay heat generated in the blanket drops by more than two orders of magnitude within an hour from its replacement. On the other hand, the decay heat generated in the shield drops by three orders of magnitude during the first day following shutdown. The reactor structure would qualify for disposal at the end of its lifetime as low level waste. Only remote maintenance could be allowed at any location inside the reactor containment.

ACKNOWLEDGEMENT

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